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LITHIUM DEPLETION BOUNDARY IN A PRE-MAIN SEQUENCE BINARY SYSTEM

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ABSTRACT

A lithium depletion boundary is detected in HIP 112312 (GJ 871.1 A and B), a $\sim$ 12 Myr old pre-main sequence binary system. A strong (EW$\approx$ 300 mÅ) Li 6708 Å absorption feature is seen at the secondary ($\sim$M4.5) while no Li 6708 Å feature is detected from the primary ($\sim$M4). The physical companionship of the two stars is confirmed from common proper motions. Current theoretical pre-main sequence evolutionary models cannot simultaneously match the observed colors, brightnesses, and Li depletion patterns of this binary system. At the age upper limit of 20 Myr, contemporary theoretical evolutionary models predict too slow Li depletion. If true Li depletion is a faster process than predicted by theoretical models, ages of open clusters (Pleiades, α Persei, and IC 2391) estimated from the Li depletion boundary method are all overestimated. Because of the importance of the open cluster age scale, development of self-consistent theoretical models to match the HIP 112312 data is desirable.

Subject headings: (stars:) binaries: visual — stars: pre-main-sequence — stars: abundances — stars: individual (WW PsA, TX PsA) — open clusters and associations: individual (β Pictoris moving group, Pleiades, α Persei, IC 2391)

1. INTRODUCTION

Gravitationally contracting low mass ($M \lesssim 1 M_\odot$) stars are fully convective (Hayashi track evolution) until they near the main sequence. As the contraction proceeds, the stellar temperature rises and when the core temperature reaches $\sim 2.5 \times 10^6$ K, depletion of lithium begins via $^7Li(p,\alpha)^4He$ reaction (Ventura *et al.* 1998, and references therein). Since the lithium burning process is very sensitive to the core temperature (burning rate $\propto T^{20}$, Bildsten *et al.* 1997), once Li burning starts, it will consume all available lithium in a very short timescale ($\lesssim$ 10 Myr). However, more massive stars ($M \gtrsim 1 M_\odot$) form radiative cores in their early evolution that results in a separation of the surface layers from the hotter inner regions. As long as the temperature at the base of the convective layer is below the Li burning temperature, surface Li can be preserved. On the other hand, if stellar mass is too low ($\lesssim 0.065 M_\odot$), a star (in fact, a brown dwarf) can never attain a high enough core temperature to burn Li; hence such brown dwarfs should always show strong Li absorption at 6708 Å. For the higher mass brown dwarfs (mass range of $0.065 M_\odot - 0.072 M_\odot$), lithium eventually can burn (Basri 2000).

Because of the fast Li burning process, the location of the Li burning boundary in a coeval stellar group should be well defined. The Li depletion boundary (LDB) of older clusters stays at $0.065 M_\odot$, since that is the mass below which brown dwarfs never get hot enough to burn lithium. This implies that the LDB age determination only works up to an age of about 250 Myr which is the age when the interior of a $\sim 0.065 M_\odot$ brown dwarf just creeps above the lithium burning temperature. LDBs of younger clusters will be located at higher masses than the LDB of old clusters because lesser mass stars take more time to reach the lithium burning temperature by gravitational contraction than more massive stars do. Once the luminosity of cluster stars at the LDB is known, the LDB location can be compared to that of theoretical models from which we can estimate the cluster age. To date, LDBs have been detected in three open clusters — Pleiades (Basri *et al.* 1996; Stauffer *et al.* 1998), α Persei (Stauffer *et al.* 1999), and IC 2391 (Barrado y Navascués *et al.* 1999). Interestingly, ages determined from the LDB method for these clusters are all $\sim$ 50% larger than traditional upper main sequence fitting ages (Table 1), and the lithium ages have generally been adopted as correct. If so, then traditional interior models for the upper main sequence must be revised.

We have detected the LDB in a pre-main sequence (PMS) binary system HIP 112312 from medium and high resolution spectroscopic observations. To date, this is the only system other than open clusters whose LDB is detected. The HIP 112312 binary system has a well determined distance from Hipparcos (d = 24 pc) and BVI_cJHK_s photometric magnitudes. Using these data, we can check if theoretical models of photometric isochrone ages and Li depletion ages are self-consistent. In this paper, we compare frequently used theoretical models with parameters derived from our observations.

2. DATA

2.1. *Observed Data*

We obtained spectra of WW PsA (=GJ 871.1 A) and TX PsA (=GJ 871.1 B) as part of an extensive on-going search for young and nearby stars to Earth (Song, Bessell, & Zuckerman, ApJ in prep.). High resolution spectra were obtained using an echelle spectrograph on the Nasmyth-B focus and medium resolution spectra were obtained with Double Beam Spectrograph (DBS) on the Nasmyth-A focus of the Australian National University's 2.3 m telescope. The red channel of the DBS covered the spectral range 6500 – 7450 Å at a measured resolu-

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TABLE 1
LI DEPLETION BOUNDARIES IN OPEN CLUSTERS

cluster name	age (Myr) UMS[a]	LDB	Li depletion boundary sp.	M_{I_c}	$(R-I)_c$	Reference
IC 2391	35	53	M5.0	10.25	1.91	Barrado y Navascués *et al.* (1999)
α Persei	70	90	M6.0	11.47	2.12	Stauffer *et al.* (1999)
Pleiades[†]	85	125	M6.5	12.20	2.20	Stauffer *et al.* (1998)

[a] These are upper main sequence fitting ages
[†] LDB of the Pleiades was first discovered by Basri *et al.* (1996) at slightly earlier spectral type

tion of 1.2 Å (0.55 Å/pixel). DBS spectra, displayed in Figure 1, have $\sim$ 5000 counts per pixel in the vicinity of 6700 Å. From these spectra, one can clearly see the non-detection and detection of the Li 6708 Å absorption feature from the primary and secondary, respectively, and strong Hα emission from both stars. Eight orders of the echelle covered portions of the spectra between 5800 and 7230 Å. At orders containing the Hα and Li 6708 Å lines, the measured resolution was 0.45 Å (0.17 Å/pixel).

All spectra were reduced following standard procedure using IRAF. We also obtained BVI_c photometric magnitudes of the binary as part of a larger photometry program (Shobbrook et al., in preparation) for young stars identified in our on-going spectroscopy program. The HIP 112312 components have JHK_s magnitudes from the 2MASS 2nd release database. Spectroscopic and photometric data are summarized in Table 2.

2.2. *Derived Data*

2.2.1. T_{eff} *and spectral types*

Some colors of the HIP 112312 binary from BVI_cJHK_s are slightly inconsistent compared to normal M dwarfs. For example, the $B-V$ of the two stars are bluer by about 0.1 mag than normal M dwarfs. The lower gravity of a young M dwarf compared to the mean gravities of ZAMS M dwarfs could account for much of this difference and a few stars in the Taurus-Auriga region studied by Kenyon & Hartmann (1995) have similarly blue $B-V$ colors for their $V-I$ colors. The Pleiades M dwarfs are also bluer in $B-V$ than one would expect for their $V-I$ or $V-K$ colors (Stauffer et al. 2002, in prep.). This is probably just a feature of young K and M dwarfs. The $V-I$ and $V-K$ colors are quite consistent and correspond to spectral types around M4 and M4.5 for HIP 112312 A and B, respectively.

TABLE 2
CHARACTERISTICS OF HIP 112312 BINARY SYSTEM

	GJ 871.1A WW PsA	GJ 871.1 B TX PsA
RA (2000)	22 : 44 : 57.94	22 : 45 : 00.04
DEC (2000)	–33 : 15 : 01.7	–33 : 15 : 26.0
Sp. type	M4e	M4.5e
V	12.16±0.03	13.42±0.02
$B-V$	1.50±0.02	1.58±0.02
$V-I_c$	2.78±0.02	3.04±0.01
J	7.78±0.02	8.68±0.02
H	7.14±0.04	8.05±0.04
K_s	6.91±0.04	7.77±0.04
R.V. (km/sec)	+2.5±0.6	-1.7±2.4
EW(Hα) Å	–6.4	–4.3
EW(Li) mÅ	<30	290
μ_α (mas/yr)	179.8±5.2	179.8±2.9
μ_δ (mas/yr)	-129.2±3.8	-126.0±3.0
TiO5 index	0.38	0.34

We also measured the TiO5 spectral index ($\equiv F[7126-7135]/F[7042-7046]$) for HIP 112312 A and B together with that for GJ 644 (an M3 standard) following Reid *et al.* (1995). The measured TiO5 index for GJ 644 (TiO5=0.48) was in good agreement with its standard value and with its $V-I$ color. Based on the TiO5 and spectral type relation of Reid *et al.* ($Spectral\,type\,subclass = -10.775 \times \mathrm{TiO5} + 8.2$), the TiO5 indices for HIP 112312 A & B again indicate M4.1 and M4.5 spectral types, respectively. From colors and TiO5 indices, we assign M4 and M4.5 spectral types to the primary and secondary, respectively.

The effective temperatures of HIP 112312 A and B from their $V-I$ and $V-K$ colors using an empirical temperature calibration and model colors (Bessell 1991) are estimated to be 3150 K and 3030 K respectively, and their uncertainties are not larger than 100 K.

2.2.2. *Lithium Abundance*

Estimation of Li abundances from observed Li 6708 Å equivalent width requires information on Li curves of growth. From synthetic model spectra (Allard et al. 2001 and private communication with P. Hauschildt for updates) for T_{eff}=3000, 3100, & 3200 K and $\log g$=4.0 & 4.5 with a range of Li abundances ($\log N(Li)$ = –99, 0.05, 0.1, 0.3, 0.5, 0.75, 1.0, & 1.3), we constructed a set of Li 6708Å curves of growth (Figure 2). We note that the indicated curves of growth take into account the effect of strong TiO band absorption features around 6708Å which can alter the lithium equivalent width measurement depending on the location of the pseudo-continuum level (Pavlenko 2002, priv. comm.). When our Li curves of growth are compared with Pavlenko's (2002, priv. comm.) model data which also takes the effect of TiO bands into account, our curves of growth differ by $\lesssim 15$ mÅ at common Li abundance points ($\log N(Li) = 1.0\,\&\,1.3$). Using the estimated effective temperature of the secondary from section 2.2.1 (3030 K) and the measured equivalent width of 290 mÅ, from Figure 2 we conservatively estimate the Li abundance of the secondary to lie in the range $\log N(Li) = 0.85-1.10$. If we adopt $\log n(Li) = 3.31$ as the interstellar Li abundance, then HIP 112312 A and B currently have only <0.01 % and $0.35-0.62$ % of their initial Li contents.

2.2.3. *Luminosities*

It is quite straightforward to calculate luminosities of the HIP 112312 binary system from Hipparcos measured parallax

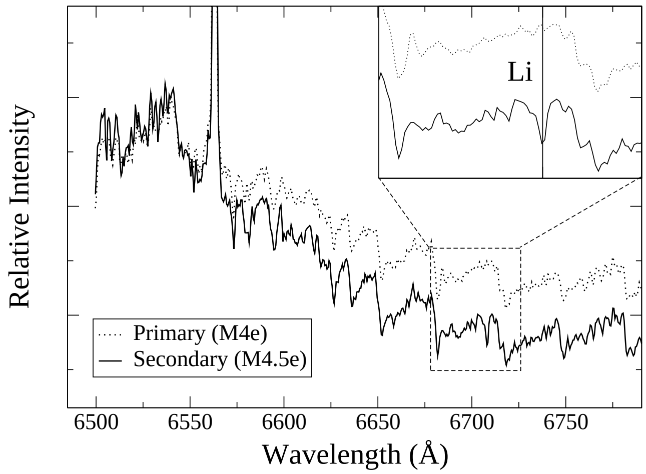

FIG. 1.— Part of the DBS spectra of the HIP 112312 system. The dotted line represents the primary spectrum and the solid line is for the secondary. The secondary spectrum shows steeper slope than the primary spectrum not because of the temperature difference, but presumably due to stronger molecular bands (i.e., CaH).

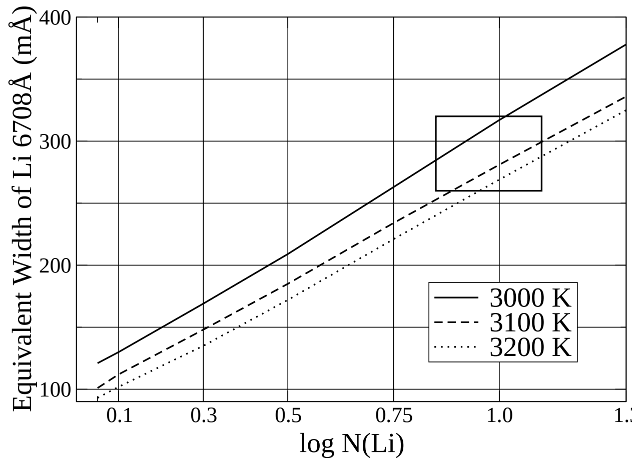

FIG. 2.— Li 6708 Å curves of growth for $\log g = 4.3$ constructed from a set of synthetic model spectra (Allard et al. 2001 and see text for details). The rectangular box represents an acceptable range of Li abundance for the secondary star of HIP 112312.

(42.4 ± 3.4 mas) and measured photometric magnitudes. In calculation of bolometric magnitudes, we use $m - M = 1.86$ for the distance modulus, $M_{bol} = 4.75$ for the Sun, bolometric correction of 2.73 and 2.77 magnitude at K band for the primary and the secondary, respectively (Bessell *et al.* 1998). The calculated bolometric magnitudes are 7.78 & 8.68 and the calculated luminosities of A & B components are $\log(L/L_{\odot}) = -1.22$ and -1.58, respectively. Uncertainty in luminosity is estimated to be $\Delta \log(L/L_{\odot}) = 0.160$ which is mainly due to the Hipparcos distance uncertainty.

2.2.4. *Space Motions*

Physical companionship of the HIP 112312 components is verified from the common proper motions of the primary and the secondary (Table 2). The proper motions listed in Table 2 are weighted means of SPM 2.0 (Platais *et al.* 1998) and UCAC1 (Zacharias *et al.* 2000) catalog values. Proper motions of the primary from Hipparcos catalog ($\mu_\alpha = 183.12 \pm 2.50$ mas/yr, $\mu_\delta = -118.87 \pm 2.21$ mas/yr) are in fair agreement with the Table 2 values.

From our echelle spectra, we determined weighted mean radial velocities of the primary and secondary from a line fitting method (see Table 2). We also estimated the rotational velocity ($v \sin i$) of the primary to be (~ 40 km/sec) but were unable to do so for the secondary because of its low S/N spectrum. Using the measured radial velocities, Hipparcos distances, and proper motions, we derived galactic space motions (U,V,W) with respect to the Sun of HIP 112312 by using the formulation of Johnson & Soderblom (1987); $(U,V,W) = (-11.8 \pm 1.2, -19.0 \pm 1.6, -11.0 \pm 0.9)\, km/sec$ for the primary and $(-13.8 \pm 1.5, -19.1 \pm 1.6, -7.2 \pm 2.2)\, km/sec$ for the secondary. Based on the similar space motions, proximity to Earth (24 pc), and very young ages ($\lesssim 20$ Myr, see Figure 3 and discussion in section 2.3), the HIP 112312 binary components may be members of the β Pictoris moving group (Zuckerman *et al.* 2001). The β Pictoris group was defined as nearby stars that have UVW velocity each within ~ 2 km/sec of those of β Pictoris, $(-10.8, -16.4, -8.9)$, and age consistent with 12 Myr (Zuckerman *et al.* 2001).

2.3. *Discussion and Comparison to Models*

We compare pre-main sequence (PMS) stellar evolutionary models with our observed HIP 112312 binary data by plotting HIP 112312 A and B on a $\log T_{eff}$ versus $\log(L/L_{\odot})$ plot along with three PMS models (Figure 3). The high luminosities of A and B clearly indicate their young age (< 20 Myr); however the scatter among the estimated ages from different models is rather large.

The three theoretical models plotted in Figure 3 also predict Li depletion patterns for PMS stars. Since we know how much Li currently remains in HIP 112312 A and B components (section 2.2.2), we can directly compare the observed Li contents to the predicted values (Table 3).

Zuckerman *et al.* (2001) identified ~ 30 co-moving stars near Earth, the β Pictoris moving group. By plotting late-type members on a color magnitude diagram with theoretical isochrones, they estimated an age of the group as ~ 12 Myr.

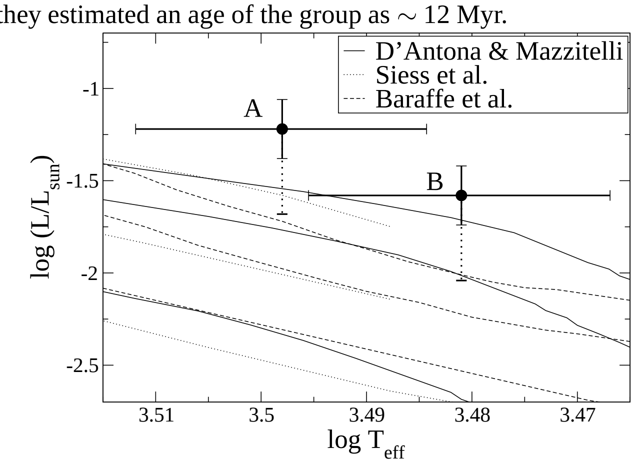

FIG. 3.— Hertzsprung-Russell diagram of the A and B components of HIP 112312 with isochrones from three different PMS theoretical stellar evolutionary models (Baraffe *et al.* 1998; D'Antona & Mazzitelli 1997; Siess *et al.* 2000). From top to bottom, 10, 20, & 100 Myr isochrones are plotted for each model. The dotted luminosity error bars indicate the case if either A or B should itself happen to be an equal mass binary. However, to the Adaptive Optics resolution at Keck, neither the primary nor the secondary is a binary (Macintosh et al., in prep.). If HIP 112312 A & B are ~ 12 Myr old, then their masses are $\sim 0.32 M_{\odot}$ and $\sim 0.18 M_{\odot}$, respectively, based on the above models.

TABLE 3

PREDICTED AND OBSERVED LI CONTENTS FOR STARS WITH $\log L/L_\odot = -1.22$ (PRIMARY) AND $\log L/L_\odot = -1.58$ (SECONDARY).

Model	age (Myr)	^{7}Li content (% of initial content) Primary	Secondary
Observed values	< 20	< 0.01	0.35 – 0.62
Baraffe *et al.* (1998)	10	~ 98	100
	20	~ 0.7	~ 56
D'Antona & Mazzitelli (1997)	10	~ 85	100
	20	< 0.01	~ 5
Siess *et al.* (2000)	10	~ 98	100
	20	< 0.01	~ 69

Note. — Among different theoretical models, D'Antona & Mazzitelli (1997) fits the observed data best and all LDB ages of open clusters were based on the D'Antona & Mazzitelli model. However, even at the age upper limit of the HIP 112312 binary system, the D'Antona & Mazzitelli model still predicts too slow Li depletion (~ 5 % of Li content for the secondary corresponding to > 600 mÅ of Li 6708 Å equivalent width).

Recently, Ortega *et al.* (2002) estimated a kinematic age of the β Pictoris moving group by tracing positions of individual members back in time. They found that the β Pictoris members occupied the smallest volume about 11.5 Myr ago; hence they assigned a kinematic age of 11.5 Myr. We obtain somewhat similar results when we trace positions of the currently known members back in time using constant velocity trajectories (i.e., no galactic potential treatment, Song et al. in prep.). Many members were more concentrated into a central cluster about 12 Myr ago although the overall size of the moving group has not been reduced as much as claimed in Ortega *et al.* (2002). The reasonably good agreement between photometric isochrone age and dynamical age of the β Pictoris group indicates that ages estimated from theoretical isochrones can be trusted in general for ~ 10 Myr old stars.

Based on the facts that the HIP 112312 A component locates on the Hertzsprung-Russell diagram above the 10 Myr isochrone and that HIP 112312 AB may belong to a large ~ 12 Myr old β Pictoris moving group (Zuckerman *et al.* 2001; Ortega *et al.* 2002), we believe that the true age of HIP 112312 cannot be older than 20 Myr. At the age upper limit of 20 Myr, all three theoretical models predict too slow Li depletion (here we assume that for given ages, theoretical model effective temperature and luminosity calculations are more reliable than lithium depletion calculations). If the true age of HIP 112312 is younger than ~ 12 Myr (as may be hinted from Figure 3), then inconsistency between photometric data and Li depletion timescales of contemporary theoretical models becomes more severe. If the true age of HIP 112312 is not significantly different from ~ 12 Myr, thus requiring a faster Li depletion process than those predicted by contemporary models to fit the observed data, then ages of open clusters (Pleiades, α Persei, and IC 2391) estimated from the LDB method are all overestimated. Since an age scale of open clusters is critical and tied into many areas of astronomy, developing self-consistent theoretical models to match the HIP 112312 binary system data is an urgent task.

Lastly, it is worthwhile mentioning that a low mass secondary component (M4.5) of a previously identified β Pictoris member (V343 Nor, K0V) also shows a similarly strong Li 6708 Å feature (Song et al, in prep.). V343 Nor B and HIP 112312 B have almost the same spectral types based on the TiO5 spectral indices and photometric colors. Study of V343 Nor B corroborates the idea of HIP 112312 being a member of the β Pictoris moving group and the location of the LDB must be at $\sim$M4.5 for 10 – 20 Myr old stars.

3. SUMMARY AND DISCUSSION

We have identified the Li depletion boundary in a < 20 Myr old pre-main sequence binary system, HIP 112312 A & B. From its galactic space motion, young age, and proximity to Earth, the HIP 112312 binary system may be a member of the ~ 12 Myr old β Pictoris moving group. At the conservative age upper limit of 20 Myr, all contemporary theoretical evolutionary models predict too slow Li depletion. Incorrect model Li depletion rates may cause overestimated open cluster ages (Pleiades, α Persei, and IC 2391) from the lithium depletion boundary method. Because of the importance of the open cluster age scale, development of self-consistent theoretical models to satisfy HIP 112312 binary system data is desirable.

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REFERENCES

Allard, F., Hauschildt, P. H., Alexander, D. R., Tamanai, A., & Schweitzer, A. 2001, ApJ, 556, 357
Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, *A&A*, **337**, 403
Barrado y Navascués, D., Stauffer, J. R., & Patten, B. M. 1999, *ApJ*, **522**, L53
Basri, G. 2000, *ARA&A*, **38**, 485
Basri, G., Marcy, G. W., & Graham, J. R. 1996, *ApJ*, **458**, 600
Bessell, M. S. 1991, AJ, 101, 662
Bessell, M. S., Castelli, F., & Plez, B. 1998, *A&A*, **333**, 231
Bildsten, L., Brown, E. F., Matzner, C. D., & Ushomirsky, G. 1997, *ApJ*, **482**, 442
D'Antona, R. A. & Mazzitelli, I. 1997, in *Cool stars in Clusters and Associations*, edited by R. Pallavicini & G. Micela, vol. 68 of *Mem.S.A.It.*, 807
Johnson, D. R. H. & Soderblom, D. R. 1987, *AJ*, **93**, 864

Kenyon, S. J. & Hartmann, L. 1995, *ApJS*, **101**, 117
Ortega, V. G., de la Reza, R., Jilinski, E., & Bazzanella, B. 2002, *ApJ*, **575**, 75
Platais, I., *et al.* 1998, *AJ*, **116**, 2556
Reid, I. N., Hawley, S. L., & Gizis, J. E. 1995, *AJ*, **110**, 1838
Siess, L., Dufour, E., & Forestini, M. 2000, *A&A*, **358**, 593
Stauffer, J. R., Schultz, G., & Kirkpatrick, J. D. 1998, *ApJ*, **499**, L199
Stauffer, J. R., *et al.* 1999, *ApJ*, **527**, 219
Ventura, P., Zeppieri, A., Mazzitelli, I., & D'Antona, F. 1998, *A&A*, **331**, 1011
Zacharias, N., *et al.* 2000, *AJ*, **120**, 2131
Zuckerman, B., Song, I., Bessell, M. S., & Webb, R. A. 2001, *ApJL*, **562**, L87